

WARM-HOT GAS IN GROUPS AND GALAXIES TOWARD H2356-309*

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Accepted to ApJ Letters

ABSTRACT

We present a detailed analysis of the galaxy and group distributions around three reported X-ray absorption line systems in the spectrum of the quasar H2356-309. Previous studies associated these absorbers with known large-scale galaxy structures (i.e., walls and filaments) along the line of sight. Such absorption lines typically trace $\sim 10^{5-7}$ K gas, and may be evidence of the elusive warm-hot intergalactic medium (WHIM) thought to harbor the bulk of the low-redshift “missing baryons;” alternatively, they may be linked to individual galaxies or groups in the filaments. Here we combine existing galaxy survey data with new, multi-object *Magellan* spectroscopy to investigate the detailed galaxy distribution near each absorber. All of these three absorption systems are within the projected virial radii of nearby galaxies and/or groups, and could therefore arise in these virialized structures rather than (or in addition to) the WHIM. However, we find no additional galaxies near a fourth “void” absorber recently found in the spectrum, suggesting that this system may indeed trace gas unassociated with any individual halo. Though the number of known systems is still small, spatial coincidences suggest that some X-ray absorbers lie in galaxy and/or group environments, though others could still trace the large-scale filamentary WHIM gas predicted by simulations.

Subject headings: cosmology: observations — intergalactic medium — large-scale structure of universe

1. INTRODUCTION

Few phenomena in modern astrophysics exhibit the maddening combination of theoretical ubiquity and observational elusiveness as the warm-hot intergalactic medium (WHIM). Although it is effectively a generic prediction of hydrodynamic simulations, containing up to 50% of the baryons in the low-redshift universe (Davé et al. 2010), decisive observational confirmation of its existence has yet to be found. At high redshifts, the IGM has long been assayed through measurements of the Lyman-alpha forest. At $z \lesssim 2$, however, this forest progressively thins to a desert: ultraviolet spectra of bright quasars reveal drastically fewer absorbers resulting in an inferred local baryon density far below what is seen at high redshift.

This discrepancy is often described as a problem of “missing baryons.” Of course, the matter traced by the high-redshift Ly α forest has not vanished, but instead has become ionized (through shock heating and photoionization from the UV/X-ray background) to the point where essentially no neutral hydrogen is left. Fortunately, at typical WHIM temperatures and densities ($T = 10^5 - 10^7$ K and $n = 10^{-6} - 10^{-4}$ cm $^{-3}$, respectively), species of common metals like carbon, oxygen, and neon retain a few electrons, in principle allowing UV and X-ray absorption line studies of the WHIM at $z < 2$ (Perna & Loeb 1998; Cen & Ostriker 1999). Such measurements are challenging (particularly at X-ray wavelengths); nonetheless, several X-ray forest lines have been reported in blind searches with ultra-deep *Chandra* and *XMM* spectroscopy (Fang et al. 2002, 2007; Nicastro et al. 2005a,b; Williams et al. 2007).

While blind searches provide an unbiased census of the

UV/X-ray absorber population, *targeted* observations reveal important information about the nature of the systems themselves. Buote et al. (2009) successfully employed this tactic with deep *Chandra* spectroscopy of the X-ray bright $z = 0.165$ quasar H2356 – 309 (H2356 hereafter), a system which has proven to be a rich laboratory for connecting putative IGM lines to large-scale galaxy structures. Not only did they detect an O VII absorption line (corresponding to $\sim 10^6$ K gas) at the redshift of the Sculptor Wall supercluster ($z = 0.03$), but follow-up studies on the same sightline by Zappacosta et al. (2010) and Fang et al. (2010) confirmed this initial detection and found two new X-ray absorption systems associated with higher-redshift walls. Conversely, Williams et al. (2010) associated a ~ 20 Mpc galaxy filament with a previously-detected X-ray absorber. While the number of detected systems is yet small, the emerging picture seems to be that warm-hot gas pervades such large-scale structures.

However, individual galaxies also host warm-hot, extended coronae (e.g. Anderson & Bregman 2010, 2011; Dai et al. 2012; Gupta et al. 2012; Mulchaey & Jeltema 2010; Williams et al. 2005), as do low-mass galaxy groups (Mahdavi et al. 2000). As with any absorption-line study, full spectroscopic information about virialized structures near the line of sight (e.g. Prochaska et al. 2011) is critical to our interpretation of the detected lines. To this end, we are undertaking a survey of galaxies around four quasars where intervening X-ray absorption systems have been reported; here we present initial results from the H2356 sightline. A concordance Λ CDM cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70$ km s $^{-1}$ Mpc $^{-1}$.

2. DATA AND GALAXY SAMPLES

Buote et al. (2009) and Zappacosta et al. (2010) (hereafter B09 and Z10 respectively) analyzed *Chandra* and *XMM-Newton* grating observations of H2356; B09 using a combined ~ 230 ksec in *Chandra*–LETG and XMM–

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* This paper includes data gathered with the 6.5 meter Magellan Telescopes located at Las Campanas Observatory, Chile.

RGS, and Z10 using a total of 600 ksec of *Chandra*–LETG observations. B09 reported the detection of a significant O VII $K\alpha$ absorption line at the redshift of the $z = 0.03$ Sculptor Wall (later confirmed with deeper data by Fang et al. 2010). Subsequently, Z10 jointly analyzed these spectra with the 2dF Galaxy Redshift Survey (2dFGRS; Colless et al. 2001) catalog to search for WHIM near other large-scale structures, detecting low-significance candidate absorption systems near the Pisces-Cetus Supercluster ($z = 0.062$) and the Farther Sculptor Wall ($z = 0.128$). In a more recent study, Zappacosta et al. (2012) reported yet another X-ray absorption line, C V at $z = 0.112$. Interestingly, this one appears to lie in a relatively empty region with the nearest galaxies > 2 Mpc away, and its redshift is marginally consistent with a large-scale filament of galaxies.

For our analysis, we extract galaxies in a $140' \times 140'$ region centered on H2356 ($\alpha = 23^{\text{h}}59^{\text{m}}07^{\text{s}}.9, \delta = -30^{\circ}37'41''$) from the 2dFGRS. This corresponds to $\sim 5 \times 5$ Mpc at $z = 0.03$, the redshift of the nearest absorption system. Since the 2dFGRS is incomplete at faint magnitudes and in crowded regions, we supplemented these public datasets with our own multi-object spectroscopic survey around this quasar. For this we employed the Inamori-Magellan Areal Camera and Spectrograph (IMACS; Dressler et al. 2011) on the 6.5 m Magellan-Baade telescope in f/2 mode with a circular, $27'$ diameter field of view. Bright galaxies were selected from the NASA/IPAC Extragalactic Database (NED), while fainter ones very close to the sightline were taken from our own Magellan imaging. Masks were observed for at least 1 hour each, employing a $300 \text{ lines mm}^{-1}$ grism covering $3900\text{--}10000 \text{ \AA}$ at a dispersion of $1.34 \text{ \AA pixel}^{-1}$. Spectra were reduced and fit using the techniques employed by Bai et al. (2010). Ultimately we obtained redshifts for 226 galaxies. Between redshifts from the literature and our own survey, our sample is at least 75% complete to $R2 < 20$, which corresponds to relatively faint absolute magnitudes ($M_r \sim -15.4, -17.0$, and -18.7 at $z = 0.030, 0.62$, and 0.128 respectively). However, most of these apparently faint galaxies are at high redshifts ($z > 0.2$). Through the combination of 2dF and IMACS spectra, selected from a variety of imaging data sets, it is unlikely that our sample is missing faint galaxies near (or bright galaxies farther from) the absorbers.

3. GALAXIES AND GROUPS NEAR THE ABSORPTION SYSTEMS

3.1. Associating absorbers with halos

Since galaxies, groups, clusters, and large-scale filaments and walls are not mutually exclusive classifications, it is often difficult (or impossible) to uniquely categorize an absorption line as arising from any one nearby structure (particularly when precise velocities are not available, as is the case with X-ray spectroscopy). However, it is possible to search for commonalities over an ensemble of systems; e.g., whether a *specific type* of galaxy or galactic system is typically found near the warm-hot gas. Broadly speaking, more massive galaxies and groups will contain more gas at larger extents, and so their warm-hot gas may be detected at higher impact parameters than that in low-mass galaxies. To take this into account, in the following analysis we adopt the host

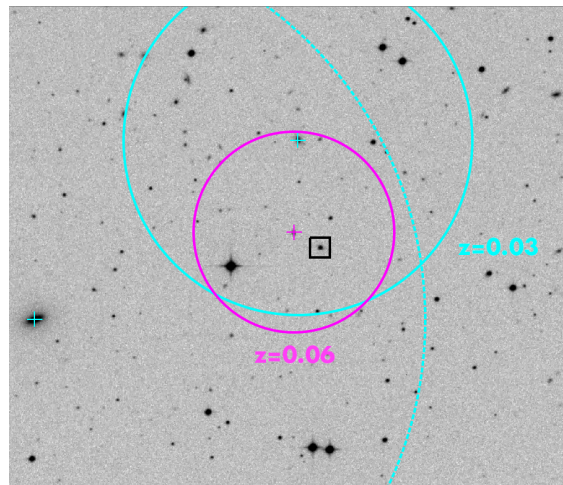


FIG. 1.— 12.5×10.8 UKST/SuperCOSMOS red image (Hambly et al. 2001a) of the field near H2356. The quasar is marked by the black square, with solid cyan and magenta circles denoting the virial radii of the nearest galaxies at $z = 0.03$ and $z = 0.062$ respectively. Additionally, the large dashed cyan arc shows the virial radius of the bright $z = 0.03$ galaxy to the left, which was included in the Y05 group catalog and is shown as a circle in Figure 2.

dark matter halo’s virial radius as a rough dividing line for “associated” vs. “unassociated” systems. Although this line is somewhat arbitrary, recent theoretical studies suggest that using R_{vir} should be a reasonable (or even conservative) criterion (e.g. Furlanetto et al. 2005; Sharma et al. 2012).

The virial radii of dark matter halos with Navarro, Frenk, & White (1996) profiles scale with mass according to the following simple relation:

$$R_{\text{vir}} = \left(\frac{2GM_{\text{vir}}}{\Delta_c H_0^2} \right)^{1/3} \quad (1)$$

where $\Delta_c \sim 100$ in the concordance Λ CDM cosmology. Following Mulchaey & Chen (2009), for each galaxy in the 2dF sample we estimate M_{vir} from the Tinker & Conroy (2009) M_r –minimum M_{halo} relation. SDSS r magnitudes are estimated with the formula

$$r = R2 + 0.07(b_J - R2) + 0.13 \quad (2)$$

which is derived from the color transformations given in Blair & Gilmore (1982) and Fukugita et al. (1996); b_J and $R2$ are photographic SuperCOSMOS magnitudes. These magnitudes have large absolute uncertainties ($\sigma_{R2} \sim 0.3$ at $19 < R2 < 20$; Hambly et al. 2001b); however, since $R_{\text{vir}} \sim M_{\text{vir}}^{1/3}$ these errors typically correspond to just $\sim 10\%$ uncertainties on R_{vir} . For comparison purposes, we additionally adopt the characteristic r –band magnitude $M_r^* = -21.21$ derived from SDSS by Blanton et al. (2003).

A significant fraction of low-redshift galaxies reside in low-mass, virialized groups, many of which have substantial reservoirs of warm-hot gas. To determine whether any of the X-ray absorbers are hosted in group-scale halos, we incorporate the 2dFGRS group catalog by Yang et al. (2005, hereafter Y05) into our analysis. In this catalog, halo masses are assigned using mass-to-light ratios inferred from the conditional luminosity function; this catalog is complete to $M_{\text{halo}} \sim 2 \times 10^{12} M_{\odot}$ at $z = 0.12$.

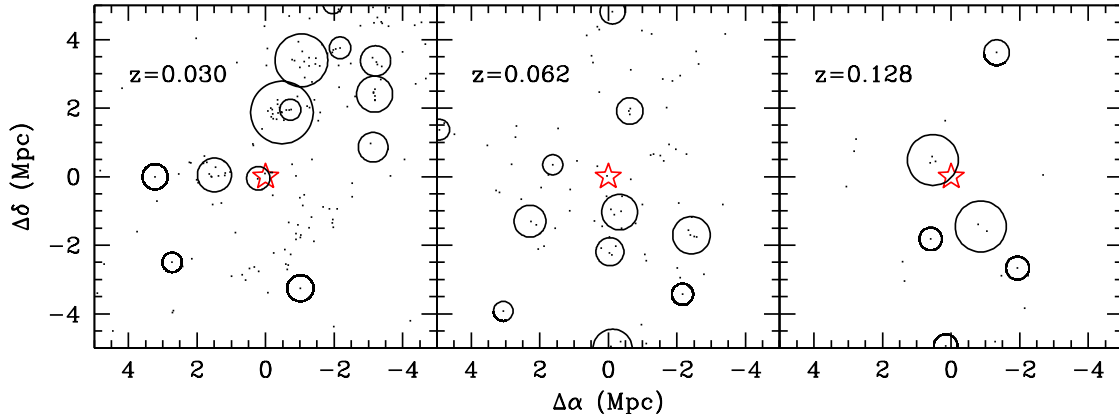


FIG. 2.— 10×10 Mpc boxes centered on the three absorption systems (in $z_{\text{abs}} \pm 0.0015$ / $v_{\text{abs}} \pm 450 \text{ km s}^{-1}$ redshift slices). Circles show groups from the Y05 2dF halo catalog, where the radius of each circle indicates the estimated virial radius of each group halo. The lowest and highest redshift absorbers lie within these projected virial radii. Given this and the individual galaxy halos shown in Figure 1, none of these three absorbers appears to be truly isolated.

We use the Y05 halo masses and equation 1 to compute group virial radii, taking the luminosity-weighted average position of the member galaxies in each group as the halo center and redshift.

3.2. Sculptor Wall, $z = 0.03$

A strong O VII absorption line at a redshift consistent with the Sculptor Wall was first reported by B09 and later confirmed by Fang et al. (2010), who measured a column density of $\log(N_{\text{OVII}}/\text{cm}^{-2}) = 16.8^{+1.3}_{-0.9}$. Figure 1 shows a close-up UKST red image of the quasar field with the nearest $z = 0.030 \pm 0.0015$ galaxies circled in cyan (each galaxy’s R_{vir} denoted by the circle’s radius). Although previous studies conclude that the absorption is associated with WHIM gas permeating the superstructure, in fact the 2dF survey shows an individual low-luminosity ($0.1L_r^*$) galaxy at the same redshift, 90 projected kpc to the north. Additionally, a significantly brighter ($1.2L_r^*$), early-type galaxy lies 240 kpc to the east. These galaxies have inferred $R_{\text{vir}} = 160$ kpc and 350 kpc, respectively, so in principle the warm-hot gas traced by the O VII could inhabit either halo (or both). Note that this more massive galaxy is also listed as a single-member group in the Y05 catalog (see Figure 2). Although our IMACS spectroscopy confirmed the 2dF redshift of the nearer galaxy, no additional nearby galaxies at this redshift were found.

3.3. Pisces-Cetus Supercluster, $z = 0.062$

Z10 searched for X-ray absorption systems at the redshift of this large-scale filament. While no individual lines were found, by jointly fitting several marginally-detected ($1 - 1.5\sigma$) lines and upper limits they infer the presence of warm-hot ($\log T = 5.35^{+0.07}_{-0.13}$) gas near the supercluster redshift. Interestingly, they also report tentative evidence for a separate hotter ($\log T \sim 7$) phase, albeit at $\sim 1\sigma$ confidence. The 2dFGRS catalog reveals a $0.25L_r^*$ disk galaxy at the absorber redshift with impact parameter 49 kpc and virial radius 197 kpc (shown in Figure 1 as a magenta cross and circle); thus, the absorber is again well within the projected virial radius of the galaxy. Our IMACS survey reveals several other galaxies within 1 Mpc, but none are likely to be associ-

ated with the absorber (Figure 3).

3.4. Farther Sculptor Wall, $z = 0.128$

This absorption system was also detected by Z10 through a joint fit to the *Chandra* spectrum over several ionic species; its significance appears to be the most marginal of the three (with inferred $\log(N_{\text{H}}/\text{cm}^{-2}) = 19.8^{+0.4}_{-0.8}$). Nonetheless, the Y05 catalog includes a group of three galaxies 724 kpc from the absorber, with a halo mass $2.3 \times 10^{13} M_\odot$ and $R_{\text{vir}} = 740$ kpc (Figure 2). Formally the absorber lies within the group’s projected virial radius; however, given the uncertainties involved, we can at most conclude that the hot gas at this redshift is marginally associated with the group halo.

Our IMACS data show several previously uncatalogued galaxies within 2 Mpc of the absorber. None is individually close enough to be associated with the hot gas; strikingly, however, they appear to form a sub-filament within the larger-scale structure of this wall, nearly centered on the quasar line of sight (Figure 3). The warm-hot gas at this redshift may therefore be associated either with the nearby group, the larger-scale filament (cf. Williams et al. 2010), or a combination of both.

3.5. A “void absorber” at $z = 0.112$?

In their recent reanalysis of the H2356 *Chandra* spectrum, Zappacosta et al. (2012) reported a 2.9σ C V absorption line at $z \sim 0.112$; notably, the nearest galaxy in 2dF at this redshift is about 2.2 Mpc away. They instead associate the absorber with a ~ 30 Mpc large-scale filament of galaxies, marginally consistent in redshift, that passes near the line of sight. We have checked our IMACS data for galaxies at this redshift that 2dF may have missed; while two galaxies indeed fall somewhat closer to the absorber (800 and 1700 projected kpc), their luminosities are low ($M_r \sim -20$ and -18 respectively). The brightest of the two has an estimated $R_{\text{vir}} \sim 300$ kpc, much smaller than the impact parameter to the quasar sightline. The combined 2dFGRS and IMACS data thus support the conclusion that this absorption line (if genuine) is not associated with a massive galaxy or group, though the possibility of an undiscovered faint nearby galaxy still remains (see Section 2). Interestingly, Tejos

et al. (2012) also estimate that about 1 in 4 Ly α absorption systems may occur in underdense regions.

4. DISCUSSION

4.1. The Mrk 421 WHIM-galaxy connection revisited

In a previous study (Williams et al. 2010), we examined the galaxy distributions around two candidate absorption systems detected in the Mrk 421 X-ray spectrum, finding a large-scale filament coincident with the system at $z = 0.027$. The two nearest galaxies lie 360 and 390 projected kpc away at the same redshift, a large enough distance that we discounted the notion of a galactic origin for that absorption system. However, these galaxies are relatively bright, the nearer of the two $M_r = -20.9$ – corresponding to $R_{vir} \sim 500$ kpc. Moreover, as these two galaxies are separated from each other by only 350 projected kpc and 8 km s^{-1} in radial velocity, they may well share a common group halo, in which case their virial radius would be even larger. Thus, under the R_{vir} criterion adopted in this paper, the $z = 0.027$ Mrk 421 system would in fact be associated with the brighter of these galaxies (or their group), not the more distant galaxy filament. In the context of the current study, where all three candidate absorption systems lie nominally within galaxy or group dark matter halos, a halo origin for the Mrk 421 absorber may in fact be more globally consistent. Interestingly, the nondetection of broad Ly α in this absorber by Danforth et al. (2011) may be indicative of higher-metallicity gas, which would be preferentially found in a bound group halo rather than a sparse intergalactic filament.

4.2. The hosts of X-ray absorption line systems

A fundamental puzzle in any IGM absorption-line study, particularly one involving metal lines, is whether the systems being measured are connected to localized phenomena like galaxies (or outflows from the same), or the more broadly distributed intergalactic medium. Since metals are strictly produced in galaxies, *all* metal-line absorption systems must in some sense have their genesis in stellar systems. Thus, the issue is really whether the observed gaseous systems are now *bound* to dark matter halos, or are instead the free-floating remnants of past outflows which have over time mixed with pristine intergalactic gas. High-redshift Ly α absorbers, even those which likely arise in the IGM, are often found to be enriched (Cowie et al. 1995; Ellison et al. 2000, but see Fumagalli et al. 2011 for a notable exception), so it stands to reason that some metal line systems could serve as signposts for the “true” IGM.

However, one unifying theme among galaxy-absorber cross-correlation studies is that *strong* absorption systems predominantly fall near galaxies. This appears to hold over a range of redshifts and ionic species, from damped Ly α /Lyman limit systems to O VI (e.g. Prochaska et al. 2011; Rudie et al. 2012; Wakker & Savage 2009). Even ions like Ne VIII, which arise primarily in 10^6 K collisionally-ionized plasma and were once thought to hold great promise for tracing the WHIM (e.g. Savage et al. 2005) in fact appear to be located in or near galaxies as well (Mulchaey & Chen 2009; Narayanan et al. 2011). Due to its tenuous and highly-ionized nature, the intergalactic medium seems to make its presence known

mostly (or exclusively) in low column density systems (like Ly α forest lines; $N_{\text{HI}} \sim 10^{14} \text{ cm}^{-2}$).

In this context, it would not be surprising if all currently known X-ray absorption line systems originate in bound systems. State-of-the-art X-ray spectrographs like *Chandra* and *XMM-Newton*, while revolutionary, are ultimately limited by the tyranny of Poisson statistics and the faintness of background AGN. Even the most exquisite grating spectra achieve sensitivities no better than $N_{\text{OVII}} \sim 10^{15} \text{ cm}^{-2}$, or an equivalent hydrogen column density of at least $N_H \sim 10^{19} \text{ cm}^{-2}$; typical deep spectra are several times less sensitive. Thus, any significant X-ray line likely represents a relatively dense, enriched system. While a fraction of these regions may exist as filaments in intergalactic space, they are almost certainly ubiquitous in the form of circumgalactic and intragroup media.

The galactic structures surrounding X-ray absorption systems, whether individual galaxies, groups, voids, or filaments, therefore play a key role in interpreting the nature of those systems. All told, four X-ray absorbers that were initially presented as evidence for the WHIM (that is, the three from Buote et al. 2009 and Zappacosta et al. 2010, along with the higher-redshift Mrk 421 absorber) may instead be associated with bound dark matter halos; two other systems ($z = 0.011$ toward Mrk 421; Nicastro et al. 2005a, and the $z = 0.112$ system of Zappacosta et al. 2012) currently have no known galaxies or groups nearby. It cannot currently be determined whether these absorbers originate in the WHIM, very faint nearby galaxies, or are themselves spurious detections. However, the emerging picture – admittedly limited by small-number statistics – suggests that a significant fraction of X-ray absorption lines are hosted in bound systems. This remaining ambiguity illustrates the need for not just deep X-ray spectroscopy of multiple background quasars, but also complete galaxy surveys around the quasar sightlines to fully assess the nature of the surrounding structure. Our Magellan/IMACS survey is ongoing; an analysis of the full galaxy sample with the most recent *Chandra* spectral data along multiple sightlines will be presented in a forthcoming paper.

Unfortunately, even with a full sample of X-ray spectra and galaxy redshifts, systematic uncertainties in the *Chandra*/LETG wavelength scale prevent us from kinematically associating absorbers with individual galaxies; in fact no new instruments with this capability are currently on the horizon. However, observations and theory suggest that warm-hot absorbers likely occur in multi-phase media (Furlanetto et al. 2005; Fox 2011). If this is the case, deep high-resolution UV spectroscopy of lower-ionization lines (e.g. C IV, O VI, Ne VIII, and broad Ly α) may reveal extended warm gaseous phases associated with the same galaxies, thereby providing a circumstantial (if not conclusive) link between the galaxies and the X-ray absorbers.

5. SUMMARY

By combining wide-field survey data from 2dF with new Magellan multi-object galaxy spectroscopy, we have presented a detailed view of the galaxy and group halo distribution around three low-redshift X-ray absorption line systems toward H2356-309. Each of these systems appears to lie within the projected virial radius of at

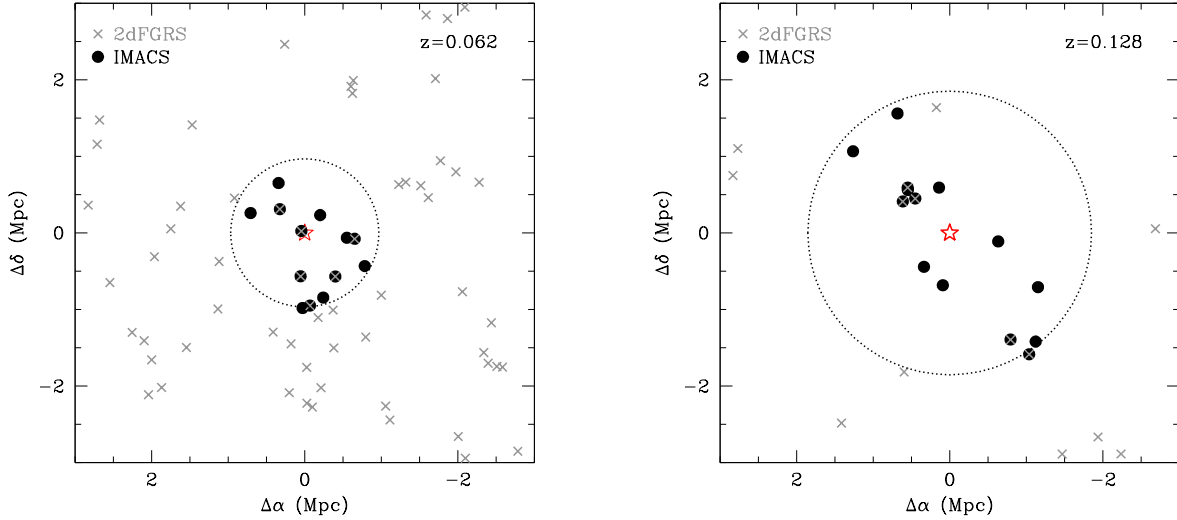


FIG. 3.— Positions of galaxies within $z_{abs} \pm 0.0015$ for the two higher-redshift absorbers, from our IMACS survey (black circles) and in the 2dFGRS catalog (grey crosses). The dotted circle shows the approximate area of the IMACS survey. The IMACS spectra confirmed the 2dFGRS redshifts of the galaxies and groups nearest the absorbers, but no new individual galaxies near the absorbers were found. If the $z = 0.128$ absorber is not associated with the three-galaxy group to the northeast (despite lying within its projected virial radius), it may instead be associated with the well-defined galaxy filament found in our IMACS survey.

least one galaxy and/or group halo at the same redshift, though for the most distant system the overlap is marginal. Though our sample is small, we conclude that a significant fraction of X-ray absorption systems may arise in bound structures, indicating that some of them may trace extended circumgalactic (and/or intragroup) media rather than the filamentary warm-hot IGM.

We thank the anonymous referee for suggestions which improved the manuscript. Support for this work was provided by the National Aeronautics and Space Administration through Chandra Award Number AR2-13016X issued by the Chandra X-ray Observatory Center, which

is operated by the Smithsonian Astrophysical Observatory for and on behalf of the National Aeronautics Space Administration under contract NAS8-03060. Partial support was also provided by NSF grant AST-0707417. This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration; and of the SuperCOSMOS Science Archive, prepared and hosted by the Wide Field Astronomy Unit, Institute for Astronomy, University of Edinburgh, which is funded by the UK Science and Technology Facilities Council.

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